87/5-15-90 JS (2)
LA-11807

*Gamma-Ray and Neutron Leakage Spectra
Calculated for Unshielded Reactors*

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James Terrell

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GAMMA-RAY AND NEUTRON LEAKAGE SPECTRA CALCULATED FOR UNSHIELDED REACTORS

by

JAMES TERRELL

ABSTRACT

The spectra of neutrons and gamma rays escaping from unshielded reactors have been calculated for a number of simplified cases. Such spectra are important in connection with reactors operating in space orbit around the earth, which would normally have little or no heavy shielding. Reactors in space, such as the Soviet RORSAT spacecraft, have caused considerable interference with the operations of other spacecraft. Knowledge of the characteristics of their leakage spectra may be useful in understanding or minimizing such interference.

The Monte Carlo Neutron-Photon (MCNP) code developed at Los Alamos has been used in these calculations. In the cases considered here the critical assembly is assumed to have spherically symmetrical geometry, with a central core of fissionable material surrounded by one or more shells of other material. The outer shells considered include beryllium, beryllium oxide, sodium, potassium, lithium, lithium hydride, and iron. The results obtained, presented as graphs, show that a number of materials that may be used in space reactors should lead to distinctive gamma-ray and neutron leakage spectra. Measurements of such spectra might well be useful in characterizing an unknown reactor type.

I. INTRODUCTION

The leakage spectra from unshielded nuclear reactors are important in connection with reactors operating in orbital space. A number of such reactors have already been put into use, primarily in Soviet Radar Ocean Reconnaissance Satellites (RORSATs). Reactor-powered satellites, such as the SP-100 test reactor, may be launched again by the United States. Such reactors would normally have little or no shielding because of weight considerations.

Little experimental work has been done on leakage spectra, it appears. Unshielded reactors are difficult to work with; such critical assemblies as Godiva, used at Los Alamos for many years, emit neutrons and gamma rays in a very short burst, leading to major problems in measuring the spectra. The calculations of such spectra that have been

done have been primarily of the group variety, in which the energy groups typically cover many MeV, and are not useful in precise evaluation of spectra from different types of reactors. A significant feature of an unshielded reactor is that the spectra are characteristic of the reactor type rather than of the shielding, and are furthermore of high intensity and relatively undegraded energy.

Unplanned observations of gamma-radiation from orbiting Soviet Cosmos/RORSAT reactors, or of positrons produced by the gamma rays, have been made, however, starting in 1980. The declassified results of such observations, made by means of the gamma-ray spectrometer on the Solar Maximum Mission satellite, have recently been published (Rieger et al. 1989, Share et al. 1989, Hones and Higbie 1989). In addition, a balloon-borne gamma-ray telescope has made spectral measurements of several simultaneously-orbiting Soviet reactors (O'Neill et al. 1989). It is not clear that individual gamma-ray lines can be identified in these spectra, except for the 511-keV positron annihilation line. However, the number and intensity of these orbiting sources have been sufficient to interfere considerably with the operations of Solar Maximum Mission, Ginga, and perhaps other satellites.

The purpose of the present calculations is to give some idea of the neutron and gamma-ray spectra to be expected from various types of unshielded reactors. The Monte Carlo Neutron-Photon (MCNP) program developed at Los Alamos has been used in these calculations. The results obtained show that a number of materials that may be used in reactors should lead to quite distinctive spectra.

II. THE MCNP PROGRAM

The MCNP program--a Monte Carlo code for neutron and photon transport--was developed at Los Alamos over the course of many years. In recent years its development has been due to the efforts of the Radiation Transport Group (X-6) of the Los Alamos National Laboratory (Briesmeister 1986). MCNP follows the paths of large numbers of individual neutrons and photons through a specified three-dimensional material assembly by means of random choices of type of interaction (fission, scattering, absorption,...), path length, scattering angle, and so on. The cross sections that determine the probabilities are based on ENDF/B-V (Evaluated Neutron Data File) evaluations (Garber 1979), and are intended to represent the best knowledge--or guesses--as to the neutron and photon interactions involved (Soran and Seamon 1980).

For photons the types of interaction used include incoherent and coherent scattering, pair production with emission of annihilation radiation, and photoelectric absorption followed by fluorescent emission of lower-energy photons. The random choices made in the Monte Carlo calculation result in spectra that have the same sort of counting fluctuations in each energy channel as in actual or hypothetical measurements, without, it is hoped, the systematic errors that characterize actual detectors. Standard deviations are calculated for each energy channel, based on the weighted number of counts. The

results in this paper are presented primarily as graphs, with a resolution of 10 keV in most cases, except where noted.

It should be noted that these MCNP calculations take no account of delayed fission gamma rays, fission-product gamma rays, or gamma rays from fissile materials (uranium and plutonium) or from reactor materials activated by neutrons. The effect of delayed fission and fission product gamma rays, in particular, would be to raise the level of the continuum. It is hoped that these omitted photons would not greatly alter the leakage spectra of a reactor in space, but in any case they would depend on the power and operational history of the reactor.

In all cases considered here, the critical assembly is assumed to have spherically symmetric geometry, with a central core of fissionable material surrounded by one or more shells of other material. The outer shells considered include beryllium, beryllium oxide, sodium, potassium, lithium, lithium hydride, and iron. An example of such a geometry is shown in Fig. 1. The radius of the central core, which is assumed to be ^{235}U in most cases, is adjusted to give approximate criticality to the assembly. The results obtained show that a number of materials that may be used in reactors should lead to quite distinctive neutron or photon spectra.

III. COMPUTED REACTOR LEAKAGE SPECTRA: ENRICHED URANIUM (GODIVA)

The simplest spherically-symmetrical case is a bare sphere of fissionable material, such as the Godiva critical assembly that has been extensively investigated at Los Alamos. This assembly, in idealized form, is a sphere of enriched uranium, taken here to be 93.77% ^{235}U , 5.20% ^{238}U , and 1.03% ^{234}U (atom fractions), with a radius of 8.7407 cm. With the density taken to be 18.742 g/cm³, this corresponds to a mass of 52.43 kg. These specifications are based on the experimental determination of the critical mass for Godiva, after correction for voids, reflection, and other departures from ideal assumptions; the result was a critical mass of 52.43 ± 0.23 kg for the density assumed here (Hansen and Paxton 1969). The multiplication factor (neutron multiplication per generation) for this geometry, for 40 generations of 3000 neutrons each, was calculated by the MCNP code to be $k = 0.997 \pm 0.002$ (the uncertainties used in this report are standard deviations).

Determination of the critical mass was not a high priority of the present calculations, but it is encouraging to note the excellent agreement of calculation and experiment: the value of k should be 1.0 for a critical mass. The neutron and gamma-ray leakage spectra, which are of most interest in this report, should be independent of the density for a critical mass of given material in a specified shape. Thus the dimensions, densities, and critical masses assumed in the calculations presented here should have no effect on the leakage spectra of photons and neutrons, so long as the assembly is critical and the relative radii and densities are unchanged.

Figure 2 shows the calculated prompt fission photon spectrum emitted by the assembly, per fission neutron. This particular calculation took 6.8 minutes on a Cray-1 computer. In MCNP calculations the fission gamma-ray spectrum is smooth and approximately exponential (Stewart and Hunter 1972), but only for fission induced by neutrons of less than 1.08 MeV energy. For neutrons of higher energy the photon spectrum produced has steps at 0.5-MeV energy intervals, above 1 MeV. Some evidence may be seen in Fig. 2 of these steps, artifacts of the calculation. They smooth out and vanish with sufficient scattering material outside the fission source.

The total yield of gamma rays is 0.137 ± 0.002 photons per fission neutron, or 0.358 photons per fission, using $\bar{\nu} = 2.616$ neutrons/fission for this case. This value of $\bar{\nu}$ is given by the MCNP calculation for this fast reactor, and is of course higher than the thermal fission value of 2.43; the value of $\bar{\nu}$ increases by about 1 neutron per 7 MeV of energy of the neutrons inducing fission (Terrell 1962, 1965).

Figure 3 shows the neutron leakage spectrum calculated for the Godiva fast reactor assembly. It is a slightly degraded version of the fission neutron spectrum, with no other characteristic features apparent. The fission neutron spectrum is well represented by a Maxwellian spectrum, $N(E) = E^{1/2}e^{-E/T}$, in which E is the neutron energy and T is a parameter equal to $2/3$ of the average energy (Terrell 1959, 1962). The average energy of fission neutrons is about 2 MeV, and the maximum in the spectrum is at about $1/3$ of the average energy, as expected for a Maxwellian distribution of fission neutrons. For Godiva the peak in the neutron leakage spectrum occurs at a lower energy, ~ 0.45 MeV from this calculation. However, the spectrum retains its exponential character, as seen in Fig. 4, a semi-logarithmic plot of the data of Fig. 3, with 100-keV resolution.

IV. ^{239}Pu CRITICAL ASSEMBLY

The photon and neutron leakage from a ^{239}Pu critical assembly were calculated by the same MCNP methods used for ^{235}U . If the density of plutonium is taken to be 19.84 g/cm^3 , a radius of 4.9 cm is found to be near-critical, with a multiplication factor $k = 0.988 \pm 0.003$, based on 40 generations of 3000 neutrons each. The total mass of this hypothetical near-critical assembly is 9.777 kg. The density assumed is that of α -phase plutonium. As Hanson and Paxton (1969) note, the critical mass is proportional to the inverse square of the density for a given shape. If the density had been taken to be that of δ -phase plutonium ($\rho = 15.61 \text{ g/cm}^3$), the corresponding near-critical mass would have been 15.79 kg. More accurate agreement with the experimental critical mass would have been obtained if the calculation had assumed a radius of 5.0 cm instead of 4.9 cm, which would then have increased the mass by $\sim 6\%$, to 16.7 kg, and might have yielded $k = 1.0$. This is in reasonable agreement with the corrected experimental result ($17.02 \pm 0.15 \text{ kg}$) found with the Jezebel critical assembly (Hansen and Paxton 1969), especially considering that the plutonium used there contained 4.5% (atom fraction) ^{240}Pu .

Figure 5 shows the gamma-ray spectrum calculated as escaping from this ^{239}Pu assembly. It is similar to that for ^{235}U , with a prominent 511-keV line due to positron annihilation, and with fluorescence lines near 100 keV.

The spectrum of neutrons escaping from this plutonium assembly is shown in Fig. 6. The spectrum is similar to that from the ^{235}U assemblies, although somewhat higher in energy, as would be expected from the higher value of $\bar{v}$, 3.181 (Terrell 1959, 1962, 1965), as well as from the smaller mass. The leakage spectra of photons and neutrons from a ^{239}Pu reactor assembly are seen to be generally very similar to those from a ^{235}U assembly, although slightly higher in average energy and number. As will be evident in the remainder of this report, much more distinctive differences in spectra are produced by the presence of other elements in the reactor, used as coolants, reflectors, or structural elements.

V. ^{235}U CRITICAL ASSEMBLY

The results to be presented in the balance of this report are based on a spherical critical assembly of pure ^{235}U (or uranium nitride in one case), surrounded by concentric spherical shells of various materials. The choice of pure ^{235}U was made, not because this material is apt to be used, but for computational simplicity. No obvious difference in the resulting spectra has been found, as may be seen in Figs. 7 and 8. The spherical radius is taken to be 8.5 cm, slightly smaller than that assumed for the Godiva assembly. This is found to give an appropriate critical multiplication factor, $k = 0.999 \pm 0.003$, for a density of 18.73 g/cm^3 and a total mass of 48.18 kg.

The photon spectrum is shown in Fig. 7, with the 10-keV resolution used in most of these calculations. In this case as in others, the spectrum above 4 MeV is not shown if there are no significant features above this energy.

Figure 8 shows the neutron leakage spectrum from the ^{235}U assembly. These results for the neutron spectrum, as for the photon spectrum, are very similar to those for Godiva.

VI. ^{235}UN CRITICAL ASSEMBLY

The leakage spectra from a sphere of uranium nitride were investigated as a slightly more complicated case. This material, in pellet form, may be used in the SP-100 space nuclear reactor. After several preliminary trials, a 12.0-cm sphere of ^{235}UN was specified, at a density of 13.6 g/cm^3 ; the nitrogen was assumed to be ^{14}N (the natural isotopic mixture is 99.63% ^{14}N). An MCNP run of 20 generations of 3000 neutrons each then gave the multiplication factor as $k = 1.029 \pm 0.003$. Thus the assumed mass of 98.44 kg (including 92.90 kg of uranium) turned out to be somewhat above critical mass; probably 11.7 cm would have been the best choice of radius.

The resultant spectrum of escaping photons is shown in Fig. 9. The results are not greatly different from the case of pure ^{235}U previously discussed.

Figure 10 shows the spectrum of escaping neutrons from this hypothetical assembly. This is noticeably different from previous cases, with a number of dips and peaks due to the presence of nitrogen.

Thus the principal difference between the leakage spectra from critical assemblies of ^{235}UN and of ^{235}U is the more irregular shape of the neutron spectrum, due to resonances in the ^{14}N cross section; a significant fraction of the fission neutrons (2.7%) are captured by the nitrogen.

VII. $^{235}\text{U} + \text{Li}$ CRITICAL ASSEMBLY

The effect of surrounding a uranium sphere with a spherical shell of lithium was investigated, using the same methods as in the simpler cases. Lithium metal has been used or proposed as a coolant for various reactors, including SP-100. For the present calculation, a shell of natural lithium with a thickness of 10 cm and density $\rho = 0.534 \text{ g/cm}^3$ is assumed to surround the ^{235}U sphere, with no gap. The uranium, with a density taken to be $\rho = 18.73 \text{ g/cm}^3$, was varied in radius until an approximately critical size was determined. The resulting radius of 8.0 cm corresponds to a critical mass of 40.17 kg. An MCNP calculation involving 40 generations of 3000 neutrons each gave the multiplication factor as $k = 1.005 \pm 0.002$.

The spectrum of escaping gamma rays, shown in Fig. 11, is similar to that found for bare spheres of ^{235}U or ^{239}Pu , except for one conspicuous difference--the huge gamma-ray peak at 0.478 MeV.

The spectrum of neutrons leaking from this hypothetical reactor is shown in Fig. 12, and is obviously much more distinctive (due to scattering in lithium) than the bare-assembly cases discussed above. It has a large low-energy peak at about 170 keV, followed by a conspicuous dip.

VIII. $^{235}\text{U} + ^7\text{LiH}$ CRITICAL ASSEMBLY

The effect of LiH as a moderator (or shadow shield, as proposed for SP-100) on these leakage spectra was investigated in another set of runs. The lithium was assumed to be isotopically separated ^7Li , in order to avoid the propensity of ^6Li for capturing neutrons. The lithium hydride shell was taken to be 10 cm thick at a density of $\rho = 0.74 \text{ g/cm}^3$, and the radius of the uranium core (with density taken to be 18.73 g/cm^3) was adjusted until the assembly was approximately critical. This resulted in a core radius of 6.7 cm and a corresponding mass of 23.60 kg, yielding $k = 1.003 \pm 0.002$ for a 40-generation run of 3000 neutrons.

Figure 13 shows the resulting gamma-ray spectrum, which is even more interesting than previous cases. The presence of hydrogen in the outer shell produces thermal neutrons for the first time in this series of calculations. The result is prominent thermal-neutron capture lines for ${}^7\text{Li}$ and ${}^1\text{H}$. Also apparent in this gamma-ray spectrum are the ~100-keV fluorescent (photoelectric) lines from uranium and the increased yield of low-energy photons (under 400 keV) also seen in the lithium-shell case (Fig. 11). These low-energy photons are produced by scattering of photons in LiH, and are scattered back into the uranium as well as to the outside, as determined from tallies at the uranium surface (not shown).

It should be noted that the gamma-ray line energies given in the caption and elsewhere in this report are the ENDF/B-V evaluations (Garber 1979) used in the MCNP code (Little 1988), and may not necessarily agree with those tabulated elsewhere, such as by Lone, Leavitt, and Harrison (1981).

The neutron leakage spectrum from this reactor assembly is shown in Fig. 14. It is quite different from previous cases because of the thermalizing effect of the hydrogen. The result is a very large low-energy yield, well off scale in the figure.

IX. ${}^{235}\text{U}$ + Na CRITICAL ASSEMBLY

The effect of sodium as a coolant on the reactor leakage spectrum was investigated in another series of runs. It was assumed that a 10-cm layer of ${}^{23}\text{Na}$, at a density $\rho = 0.971 \text{ g/cm}^3$, surrounds the ${}^{235}\text{U}$ core. Near-criticality was found to occur for a radius of 8.0 cm for the uranium, corresponding to a mass of 40.17 kg; the multiplication factor was found to be $k = 0.998 \pm 0.002$, from a 40-generation run of 3000 neutrons.

Figure 15 shows the resultant gamma-ray leakage spectrum. Downscattering has had a noticeable effect, but its most conspicuous feature is the 440-keV line due to inelastic scattering of neutrons in ${}^{23}\text{Na}$.

The spectrum of neutrons escaping from this critical assembly, shown in Fig. 16, is distinguished by a number of prominent dips and peaks due to resonances.

X. ${}^{235}\text{U}$ + K CRITICAL ASSEMBLY

The effect of potassium as a coolant on the leakage spectra was investigated in an MCNP calculation using 40 generations of 3000 neutrons. The ${}^{235}\text{U}$ core was assumed to be a sphere of 8.0 cm radius, surrounded by a spherical shell of potassium, 10 cm thick, with density $\rho = 0.862 \text{ g/cm}^3$. The mass of uranium amounted to 40.17 kg; the assembly was found to be slightly subcritical, with $k = 0.966 \pm 0.002$.

Figure 17 shows the calculated spectrum of escaping gamma rays, which is characterized primarily by a number of inelastic scattering lines.

The spectrum of leakage neutrons, shown in Fig. 18, is similar to a slightly degraded fission neutron spectrum, except for resonance structure near the peak.

An MCNP run was also made using a spherical shell of a sodium-potassium (NaK) mixture, which has been used in some reactors for cooling. As might be expected, the effects on the photon and neutron leakage spectra (not shown) combined the characteristics of the two metals as described above.

XI. ^{235}U + Be CRITICAL ASSEMBLY

The effect of beryllium as a reflector of leakage neutrons was investigated in another MCNP run, involving 29 generations of 6000 neutrons each; this run, involving more than the usual number of neutron tracks, took 19.7 minutes of Cray-1 time. It was assumed that the ^{235}U core ($\rho = 18.73 \text{ g/cm}^3$) was surrounded by a spherical shell of ^9Be , 10 cm thick, at a density of 1.848 g/cm^3 . Criticality of this assembly ($k = 0.997 \pm 0.002$) was found to occur for a core radius of 5.6 cm of uranium (13.78 kg). Thus the beryllium reflector had a large effect in decreasing the critical mass of uranium, as expected, from the unreflected value of 48.18 kg.

The resultant gamma-ray spectrum, shown in Figs. 19 and 20, is considerably different from previous cases. This and other cases involving beryllium are characterized by strong downscattering of the escaping photons.

The spectrum of escaping neutrons, shown in Fig. 21, is also quite different from previous cases, with the exception of ^7LiH (Fig. 14). Strong scattering of fission neutrons produces a very high peak at low energies, off scale in this figure. Thus the neutron spectrum for a beryllium-reflected critical assembly should be quite distinctive, and would doubtless be so even for a thinner reflector.

XII. ^{235}U + BeO CRITICAL ASSEMBLY

A beryllium reflector might well be made of BeO; thus an MCNP run was made to investigate the resultant spectra, using 40 generations of 3000 neutrons each. The ^{235}U core was surrounded by a BeO shell 10 cm thick, of density $\rho = 3.01 \text{ g/cm}^3$. Criticality ($k = 1.000 \pm 0.002$) was found to occur for a 5.3 cm radius of the uranium sphere, for a resultant critical mass of 11.68 kg.

The gamma-ray spectrum for this case, shown in Figs. 22 and 23 (both with 10-keV resolution), is in most respects similar to the leakage spectrum for a pure beryllium reflector.

The neutron leakage spectrum for BeO (Fig. 24) is somewhat similar to the beryllium-reflector case, though more complicated. In addition to the absorption dips due to beryllium resonances there are a number of conspicuous dips due to oxygen.

XIII. $^{235}\text{U} + \text{Na} + \text{Be}$ CRITICAL ASSEMBLY

An MCNP run was made to investigate the combination of sodium coolant and beryllium reflector, for a critical assembly. The ^{235}U core was assumed to be surrounded by a shell of sodium 5.0 cm thick ($\rho = 0.971 \text{ g/cm}^3$), and by an outer shell of beryllium 10 cm thick ($\rho = 1.848 \text{ g/cm}^3$). Criticality ($k = 1.001 \pm 0.002$) was found to occur for a core radius of 6.5 cm, corresponding to a critical mass of 21.55 kg. This longer MCNP run took 25.38 minutes of Cray-1 time to cover 60 generations of 3000 neutrons each.

The resultant gamma-ray leakage spectrum, shown in Figs. 25 and 26, has more similarity to the $^{235}\text{U} + \text{Be}$ case (Fig. 19 and 20) than to the $^{235}\text{U} + \text{Na}$ case (Fig. 15).

The neutron leakage spectrum, shown in Fig. 27, is very similar to that for the beryllium reflector alone (Fig. 21), with the huge peak at low energies and the same minima due to resonances.

XIV. $^{235}\text{U} + \text{K} + \text{Be}$ CRITICAL ASSEMBLY

A similar investigation was made for spherical shells of potassium and beryllium surrounding the ^{235}U core. The potassium was taken to be 5 cm thick, with density $\rho = 0.862 \text{ g/cm}^3$, and the outer beryllium shell 10 cm thick, with $\rho = 1.848 \text{ g/cm}^3$. The calculation (60 generations of 3000 neutrons each) was done for the slightly supercritical ($k = 1.010 \pm 0.002$) assumption of a 6.7-cm radius uranium core ($\rho = 18.73 \text{ g/cm}^3$, corresponding to 23.60 kg).

The resulting spectrum of escaping photons, shown in Figs. 28 and 29, has a general resemblance to the previous $^{235}\text{U} + \text{Na} + \text{Be}$ run, although the low-energy peak around 50 keV is somewhat less prominent. The most significant difference is the large number of sharp spectral lines for this case. It is not likely, of course, that experimental observations, perhaps under difficult conditions, would exhibit similarly high energy resolution (10 keV in both Figs. 28 and 29).

The neutron leakage spectrum, shown in Fig. 30, is rather similar to that for $^{235}\text{U} + \text{Na} + \text{Be}$ (Fig. 27), with minima at 0.63, 0.82, and 2.7 MeV due to beryllium resonances.

XV. ^{235}U + Fe + Be CRITICAL ASSEMBLY

A final MCNP run was made for a reactor assembly including iron, since this element is likely to be used as structural material. The iron was taken to be present as a 5-cm thick shell ($\rho = 7.874 \text{ g/cm}^3$), surrounded by an outer shell of beryllium ($\rho = 1.848 \text{ g/cm}^3$) also 5 cm thick. Criticality was found for a ^{235}U core of 6.5 cm radius ($k = 1.002 \pm 0.002$), giving a critical mass of 21.55 kg. The MCNP run involved 50 generations of 3000 neutrons.

The escaping photon spectrum, seen in Figs. 31 and 32, is conspicuous for the large number of sharp spectral lines, mostly due to inelastic neutron scattering in iron. The most conspicuous feature of the spectrum is the strong inelastic scattering line at 847 keV, but numerous other inelastic lines are also visible. Four beryllium capture lines are noticeable. It is not clear why some beryllium lines are apparent in some spectra and not in others. There may be differences in the spectrum of neutrons interacting, particularly if nonthermal reactions occur, or statistical fluctuations may be responsible in some cases.

The broad peak around 100 keV is due to Compton downscattering in the beryllium, as has been verified by determination of the spectrum of photons entering the iron from the outer beryllium shell (not shown). The photon spectrum leaving the uranium has prominent fluorescence lines near 100 keV, and a much more prominent 511-keV positron line than finally escapes from the reactor assembly (also not shown, but similar to the spectrum from bare ^{235}U , Fig. 7).

The spectrum of neutrons escaping from this assembly is shown in Fig. 33, and is largely similar to that from other critical assemblies using beryllium reflectors.

A short run made for ^{235}U + Mo revealed no distinctive features in the leakage spectra.

XVI. CONCLUSIONS

The numerous hypothetical reactor (critical assembly) cases considered in this paper are not intended to be exhaustive, merely representative. It is not likely that any of these graphs will coincide with actual experimental data when obtained, particularly in terms of available energy resolution, but it is hoped that some features at least will turn out to be characteristic of the reactor materials. The distinctive features shown here in many neutron or photon spectra may well be useful in characterizing an unknown reactor type if data should become available.

XVII. ACKNOWLEDGEMENTS

For assistance with the MCNP code I am indebted to a number of persons in Group X-6 of Los Alamos National Laboratory, especially to John S. Hendricks, Robert C. Little, Robert G. Schrandt, and Robert E. Seamon. Valuable advice on reactor properties has been given to me by Joseph L. Sapir, Ellen M. Leonard, Dale M. Holm, Thomas F. Wimett, Gordon E. Hansen, and David R. Smith, all of this Laboratory. This work was stimulated by the continuing interest of W. Robert Scarlett and George J. Berzins, of SST-Division, and was supported by the U.S. Department of Energy.

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Figure 1: Example of a critical assembly ($^{235}\text{U} + \text{Na} + \text{Be}$), simplified to spherical geometry for MCNP calculations.

GODIVA (U235 93.77%, 8.74CM RADIUS)

Figure 2: GODIVA. The spectrum is essentially a fission gamma-ray spectrum, modified by absorption and scattering. Clearly apparent here are the sharp line at 0.511 MeV due to pair-production absorption of photons (0.002 positron-annihilation photons per fission neutron), and fluorescent photons of 98, 115, and 117 keV (Little 1988) produced by the photoelectric absorption process in ^{235}U . Some evidence may be seen of steps at 0.5-MeV energy intervals above 1 MeV, which are artifacts of the calculation. They smooth out and vanish with sufficient scattering material outside the fission source. The energy resolution of the results shown is 10 keV; actual experimental results would undoubtedly be less well resolved. The total yield of gamma rays is 0.137 ± 0.002 photons per fission neutron, or 0.358 photons per fission, using $\bar{\nu} = 2.616$ neutrons/fission for this case. The average energy of the leakage photons is 1.364 MeV.

GODIVA (U235 93.77%, 8.74CM RADIUS)

Figure 3: GODIVA. The spectrum of leakage neutrons is a slightly degraded fission-neutron spectrum, shown here with 10-keV energy resolution. The total number of neutrons escaping is calculated to be 0.578 ± 0.001 per fission neutron, or 1.51 per fission, including some (n,2n) neutrons. One neutron per fission is, of course, absorbed in producing the next fission, so that almost all of the rest of the 2.616 fission neutrons escape in this case. The average energy of the neutrons leaking out is found here to be 1.689 MeV, somewhat reduced from the 2.047 MeV initial average energy.

GODIVA (U235 93.77%, 8.74CM RADIUS)

Figure 4: GODIVA. The neutron spectrum of Fig. 3 shown as a semi-logarithmic plot, with energy resolution of 100 keV (the usual energy resolution in these figures is 10 keV). The "particles" in the ordinate captions of all these figures are fission neutrons.

PU239 4.9CM RADIUS

Figure 5: ^{239}Pu . The leakage gamma-ray spectrum is similar to that for ^{235}U , with a prominent 511-keV line due to positron annihilation (0.003 photons/neutron), and fluorescence lines near 100 keV. The energies of these fluorescent photons as used in MCNP calculations are 17, 100, 103, 117, and 121 keV (Little 1988). The average energy of this spectrum is 1.387 MeV. The number of photons escaping is found to be 0.200 ± 0.002 per fission neutron, or 0.636 ± 0.006 per fission using the calculated value $\bar{\nu} = 3.181$ (the thermal value is 2.891). The larger number of photons escaping than for the ^{235}U case is doubtless due to the smaller size of the critical assembly.

PU239 4.9CM RADIUS

Figure 6: ^{239}Pu . The neutron spectrum has a peak near 0.5 MeV and an average energy of 1.9338 MeV, reduced somewhat from the initial value, 2.159 MeV. The spectrum is similar to that from the ^{235}U assemblies, although somewhat higher in energy, as would be expected from the higher value of $\bar{\nu}$, 3.181 (Terrell 1959, 1962, 1965). The number of neutrons escaping is found to be 0.676 ± 0.001 per fission neutron, or 2.152 per fission.

U235 (R=8.5CM)

Figure 7: ^{235}U . Photon leakage spectrum, with 10 keV resolution. The spectrum is essentially indistinguishable from that for the Godiva assembly (Fig. 2), except for larger statistical fluctuations due to a shorter Cray-1 run (92 seconds, for 10 generations of 3000 neutrons each). The gamma-ray spectrum, as in Fig. 2, exhibits the positron annihilation line at 511 keV (0.003 photons/fission neutron) and the fluorescent lines around 100 keV. The average photon energy is 1.382 MeV in this case. The number of photons escaping is 0.146 ± 0.003 per fission neutron, or 0.380 per fission, using $\bar{\nu} = 2.611$ neutrons/per fission as given by this calculation. These results are all essentially the same as for the Godiva assembly, with 94% ^{235}U .

Figure 8: ^{235}U . Neutron leakage spectrum. The average energy for this neutron spectrum is 1.703 MeV, reduced by scattering from the initial value of 2.037 MeV. The average number of neutrons escaping from the assembly is found to be 0.579 ± 0.002 per fission neutron, or 1.51 per fission. This is essentially the same as for the Godiva assembly (Fig. 3), except for the expected larger statistical fluctuations.

U235N 12.0CM RADIUS

Figure 9: ^{235}UN . The photon spectrum is essentially indistinguishable from that for ^{235}U alone (Figs. 2 and 7), with the same photoelectric fluorescence and positron annihilation lines. The total yield of escaping photons is found to be 0.135 ± 0.002 photons per fission neutron, with an average energy of 1.356 MeV.

U235N 12.0CM RADIUS

Figure 10: ^{235}UN . The neutron spectrum is noticeably different from previous examples, with a number of obvious dips and peaks due to resonances in the neutron total cross section of nitrogen (BNL 325). The dips in the neutron spectrum occur at energies of 0.43, 0.64 (following a peak at 0.61), 1.04, 1.12 MeV, and a number of less pronounced locations. The neutron yield is 0.532 ± 0.001 per fission neutron, with an average energy of 1.629 MeV for the escaping neutrons, compared to the 2.026 MeV initial energy, and with $\bar{\nu} = 2.520$.

U235+LI 8CM+10CM

Figure 11. $^{235}\text{U} + \text{Li}$. The photon spectrum has a huge peak at 0.478 MeV, with a strength of 0.024 photons per fission neutron. This sharp line is produced in part by inelastic scattering of neutrons in ^7Li , which makes up 92.5% (atom fraction) of natural lithium. Much of the strength of this line is also due to capture of 1.6% of the fission neutrons by the 7.5% of ^6Li present, which excites the same level in ^7Li . The capture of neutrons by ^7Li here is negligible (0.000005 captures per fission neutron). The capture of neutrons by ^6Li is, of course, the reason why isotopically separated ^7Li is preferred as a coolant. The gamma-ray spectrum includes the usual fluorescence photons at about 100 keV, and the positron annihilation line at 511 keV, at a strength of 0.0013 photons per fission neutron. The integrated gamma-ray spectrum gives a total yield for this assembly of 0.204 ± 0.002 photons/neutron, with an average energy of 1.073 MeV.

U235+LI 8CM+10CM

Figure 12: $^{235}\text{U} + \text{Li}$. The distinctive neutron spectrum includes many more low-energy neutrons, due to scattering in lithium. There is also a very conspicuous dip in the vicinity of 0.26 MeV, which is the position of a large peak in the ^6Li and ^7Li total cross sections, as well as in the $^6\text{Li}(n,t)\alpha$ cross section (BNL 325). The total number of neutrons escaping is found to be 0.559 ± 0.001 per fission neutron, with an average energy of 1.361 MeV. The initial energy of these neutrons was 2.052 MeV, with $\bar{\nu} = 2.590$.

U235+LIH 6.7CM+10CM (LI7)

Figure 13: $^{235}\text{U} + ^7\text{LiH}$. The photon spectrum shows prominent thermal neutron capture lines. The ^7Li capture line, at 2.073 MeV, has a total yield of 0.0068 photons/neutron; the ^1H capture line at 2.225 MeV amounts to 0.057 photons/neutron. The fractional loss of fission neutrons to such captures amounts to 0.0136 in ^7Li and 0.125 in ^1H . This large influence of ^1H capture is of course a good reason for using deuterium in reactors. The $^7\text{Li}(n,n')$ inelastic scattering line at 0.478 MeV is still prominent (0.015 photons/neutron) as in the previous case. The positron annihilation line at 0.511 MeV has a strength in this case of 0.005 photons/neutron. There is also an inconspicuous line at 1.052 MeV due to capture of neutrons in ^7Li . The total gamma-ray photon yield for this ^7LiH case amounts to 0.566 ± 0.003 photons/neutron; the average energy of the photons is 1.111 MeV.

U235+LIH 6.7CM+10CM (LI7)

Figure 14: $^{235}\text{U} + ^7\text{LiH}$. The neutron leakage spectrum is quite different from any calculated in previous cases because of the neutron downscattering and thermalizing occurring in the hydrogen. The conspicuous dip at 0.26 MeV, due to the neutron total cross section peak in ^7Li , is as obvious as in the previous case (Fig. 12). However, the present spectrum rises to a tremendous peak at the lowest energies, and there is a significant near-thermal component of neutrons (energy < 1 keV) amounting to 0.212 ± 0.001 escaping per fission neutron. The thermal peak is thus well off scale in this figure. The total yield of leakage neutrons integrates to a value of 0.413 ± 0.001 per fission neutron, of which more than half are thus near-thermal. The average energy of the neutrons escaping is 0.627 MeV, considerably reduced from the initial fission neutron energy of 2.038 MeV, with $\bar{\nu} = 2.558$.

U235+NA 8CM+10CM

Figure 15: $^{235}\text{U} + \text{Na}$. The photon spectrum includes the usual broad fission gamma-ray spectrum, with a considerable number of photons reduced to energies < 500 keV, as well as a small 100-keV peak and the 511-keV line at 0.0015 photons/neutron. The most conspicuous feature is the 440-keV line (0.016 photons per fission neutron), due to inelastic scattering of neutrons in ^{23}Na . The wide base around this line is not understood. The average energy of the leakage photons is 0.944 MeV, and the yield is calculated to be 0.234 ± 0.002 per fission neutron.

U235+NA 8CM+10CM

Figure 16: $^{235}\text{U} + \text{Na}$. The neutron spectrum is generally similar to the spectrum from bare critical assemblies, except for the presence of a number of prominent dips and peaks caused by resonances in the ^{23}Na total neutron cross section (BNL 325). Minima appear in this spectrum at 0.053, 0.21, 0.24, 0.30, 0.40, 0.45, 0.70, 0.79, 0.90, and 1.60 MeV. There is also a conspicuous peak at 0.52 MeV due to the corresponding minimum in the ^{23}Na neutron cross section. The average energy of these escaping neutrons is 1.542 MeV, and the yield is calculated to be 0.578 ± 0.001 neutrons per fission neutron. The initial energy of these neutrons was 2.051 MeV, with $\bar{\nu} = 2.611$.

U235+K 8CM+10CM

Figure 17: $^{235}\text{U} + \text{K}$. The photon leakage spectrum is characterized by a number of inelastic scattering photon lines, in addition to the usual 511-keV positron-annihilation line. The $\text{K}(n,n')$ lines have energies of 2.526, 2.817, 3.021, 3.603, 3.879, and 3.935 MeV (Little 1988). The strongest of these lines (2.817 MeV) has a yield of 0.0013 photons per fission neutron. All these lines are due to inelastic scattering in ^{39}K (Durell et al. 1974), which constitutes 93.2% (atom fraction) of natural potassium. The average energy of this spectrum is 1.201 MeV, and the yield is calculated as 0.146 ± 0.002 photons per fission neutron.

U235+K 8CM+10CM

Figure 18: $^{235}\text{U} + \text{K}$. The spectrum of escaping neutrons has the general appearance of a slightly degraded fission-neutron spectrum, except for a more complicated structure near the peak of the spectrum. There are minor peaks at 0.26, 0.32, and 0.42 MeV (or, conversely, minima at 0.25, 0.28, 0.30, 0.36, and 0.49 MeV), plus less prominent variations, all evidently due to resonances in the potassium neutron cross section (BNL 325). The yield of these escaping neutrons is 0.586 ± 0.001 per fission neutron, and the average energy is 1.632 MeV, compared to the initial fission spectrum energy of 2.034 MeV ($\bar{\nu} = 2.700$).

U235+BE 5.6CM+10CM

Figure 19: $^{235}\text{U} + \text{Be}$. The photon leakage spectrum has a prominent broad maximum in the spectrum at ~ 60 keV, extending up to 20 keV, evidently due to multiple Compton scattering of fission gamma rays in the beryllium. The external yield of photons amounts to 0.343 ± 0.002 per fission neutron, and the average energy is reduced to 0.920 MeV. In addition to the usual 511-keV positron decay line, there are sharp spectral lines due to neutron capture in ^9Be at 3.368, 3.444, and 6.810 MeV (see Fig. 20).

Figure 20: $^{235}\text{U} + \text{Be}$. Escaping gamma rays in this figure represent the same data as in Fig. 19, except that a broader energy range is shown. There are lines due to neutron capture in beryllium at 3.368, 3.444, and--most prominently--at 6.810 MeV. The yield of this highest-energy line amounts to 0.00053 photons per fission neutron. It should be noted that the energy resolution here is 20 keV, which makes sharp spectral lines appear lower in yield than with the 10-keV resolution used in most other figures.

U235+BE 5.6CM+10CM

Figure 21: $^{235}\text{U} + \text{Be}$. The neutron leakage spectrum shows a tremendous maximum at the lowest neutron energies, because of multiple scattering of the fission neutrons in the beryllium reflector. The neutron spectrum below 80 keV, off scale in this figure, rises to a value of 7.5/MeV for the 1-10 keV range, and to 135/MeV below that. The total yield of neutrons for this case is 0.584 ± 0.001 per fission neutron, of which 0.135 ± 0.001 have energy less than 1 keV. The neutron spectrum also shows conspicuous minima at 0.63, 0.82, and 2.7 MeV, all due to resonances in the ^9Be neutron cross section (BNL 325). There is a broad maximum near 1.5 MeV due to a minimum in the neutron cross section. The average energy of escaping neutrons for this case is 0.688 MeV, considerably reduced from the initial value of 2.027 MeV. The average number of neutrons per fission is $\bar{\nu} = 2.570$, of which 2.51% are captured in the beryllium.

U235+BeO 5.3CM+10CM

Figure 22: $^{235}\text{U} + \text{BeO}$. The photon leakage spectrum is rather similar to that for pure beryllium (Figs. 19 and 20), except for the lower intensity and the less visible lines. The yield of photons is found to be 0.248 ± 0.002 per fission neutron, with an average energy of 0.843 MeV. The sharp spectral lines seen for $^{235}\text{U} + \text{Be}$ (3.368, 3.444, and 6.810 MeV) are still present, but at reduced intensity. The spectrum above 4 MeV is displayed in Fig. 23.

U235+BeO 5.3CM+10CM

Figure 23: $^{235}\text{U} + \text{BeO}$. The photon leakage spectrum is the same as in the previous figure, with the same 10-keV resolution, but covering a wider energy range. The sharp lines are noticeably reduced in intensity from the pure beryllium case. The 6.810-MeV line from neutron capture in Be, for example, is reduced to 0.00022 ± 0.00004 photons per fission. An additional line is seen at 6.131 MeV, with equal intensity, from inelastic neutron scattering in ^{16}O .

U235+BeO 5.3CM+10CM

Figure 24: $^{235}\text{U} + \text{BeO}$. The neutron leakage spectrum has the features of the pure beryllium case (Fig. 21), plus additional characteristics due to oxygen. There is a similar peak at low energies, with an average energy of 0.693 MeV. The total yield is 0.570 ± 0.001 leakage neutrons per fission neutron, of which 0.116 ± 0.001 have energy less than 1 keV. The neutron spectrum has, in addition to the dips at 0.63, 0.82, and 2.7 MeV seen for beryllium absorption, conspicuous minima at 0.44, 0.99, 1.31, 1.65, 1.84, and 1.91 MeV, plus a peak at 2.35 MeV. All these are believed due to peaks and dips in the ^{16}O neutron cross section (BNL 325). The average energy of the initial fission neutron spectrum was 2.048 MeV, with $\bar{\nu} = 2.563$.

U235+NA+BE 6.5CM+5CM+10CM

Figure 25: ^{235}U + Na + Be. The photon leakage spectrum has considerable similarity to the beryllium-reflector case without sodium (Figs. 19 and 20). There is a broad maximum at ~50 keV and the usual 511-keV positron annihilation line, overshadowed by the 440-keV line due to inelastic scattering in sodium (with yield 0.0013 ± 0.0001 per fission neutron). Noticeable high-energy lines due to thermal neutron capture in sodium are seen at 3.370, 3.588, 3.981, 5.618, and 6.396 MeV (see also Fig. 26). These lines would not have been evident without the low-energy neutrons produced by the beryllium reflector. Also apparent are beryllium neutron-capture lines at 2.590, 3.368, 3.444, and particularly 6.810 MeV (with an intensity of 0.0013 ± 0.0001 photons per neutron). The total yield of photons amounts to 0.364 ± 0.002 per fission neutron, and the average energy is 0.806 MeV.

Figure 26: $^{235}\text{U} + \text{Na} + \text{Be}$. The photon leakage spectrum represents the same data as in the previous figure, except for lower energy resolution (20 keV instead of 10 keV) and the wider energy range, showing the higher-energy capture lines at 5.618, 6.396, and 6.810 MeV.

U235+NA+BE 6.5CM+5CM+10CM

Figure 27: $^{235}\text{U} + \text{Na} + \text{Be}$. The spectrum of escaping neutrons shown here is reminiscent of the $^{235}\text{U} + \text{Be}$ result (Fig. 21), with its huge peak at the lowest energies due to the beryllium reflector. There are also, as before, the minima due to beryllium resonances at 0.63, 0.82, and 2.7 MeV, and the broad maximum near 1.5 MeV. The total yield of escaping neutrons amounts to 0.572 ± 0.001 per fission neutron, of which 0.193 ± 0.001 have energy < 1 keV. The average energy of this leakage-neutron spectrum is 0.570 MeV, much reduced from its initial value of 2.035 MeV, with $\bar{v} = 2.570$.

U235+K+BE 6.7CM+5CM+10CM

Figure 28: $^{235}\text{U} + \text{K} + \text{Be}$. The most significant difference of this photon leakage spectrum from most other cases is the large number of sharp spectral lines, due to capture (doubtless for near-thermal neutrons) or inelastic scattering in potassium. The 0.511-keV positron annihilation line is present, as usual. There are potassium neutron-capture lines at 0.768, 1.618, 2.590 (also due to beryllium), 2.998, 3.040, 3.380 + 3.398, 3.598, 3.630, 4.002, 4.138, 4.388, 4.500, 4.658, 4.770, 5.018, 5.058, 5.178, 5.388, 5.508, 5.569, 5.746, 7.000, 7.768, and 9.390 MeV (see Fig. 29 for lines above 4 MeV). Also evident are potassium inelastic scattering lines at 2.526, 2.817, and 3.021 MeV. Beryllium neutron-capture lines appear at 2.590, 3.368, 3.444, 5.958, and most strongly at 6.810 MeV. The total yield of escaping photons amounts to 0.297 ± 0.002 photons per fission neutron, with an average energy of 0.954 MeV.

U235+K+BE 6.7CM+5CM+10CM

Figure 29: $^{235}\text{U} + \text{K} + \text{Be}$. The spectrum of leakage photons is the same as in Fig. 28, with the same 10-keV resolution, but shown here up to 8 MeV. There are potassium neutron-capture lines visible at 0.768, 1.618, 2.590 (also due to beryllium), 2.998, 3.040, 3.380 + 3.398, 3.598, 3.630, 4.002, 4.138, 4.388, 4.500, 4.658, 4.770, 5.018, 5.058, 5.178, 5.388, 5.508, 5.569, 5.746, 7.000, 7.768, and 9.390 MeV, the last line not appearing in the figure. Also evident are potassium inelastic scattering lines at 2.526, 2.817, and 3.021 MeV. Beryllium neutron-capture lines appear at 2.590, 3.368, 3.444, 5.958, and most strongly at 6.810 MeV (with yield 0.0010 ± 0.0001).

U235+K+BE 6.7CM+5CM+10CM

Figure 30: $^{235}\text{U} + \text{K} + \text{Be}$. The neutron leakage spectrum is rather similar to that for $^{235}\text{U} + \text{Na} + \text{Be}$ (Fig. 27), with minima at 0.63, 0.82, and 2.7 MeV due to beryllium resonances. The total yield is 0.561 ± 0.001 neutrons per fission neutron, and the average energy amounts to 0.603 MeV, much reduced from the initial average energy of 2.035 MeV, with $\bar{\nu} = 2.550$. Of these escaping neutrons a considerable portion (0.176 ± 0.001) have <1 keV energy. Thus these near-thermal neutrons reach a level of 176 neutrons/MeV, well off scale in this figure.

U235+FE+BE 6.5CM+5CM+5CM

Figure 31: $^{235}\text{U} + \text{Fe} + \text{Be}$. Spectrum of escaping photons. The most prominent line, by far, is the $^{56}\text{Fe}(n,n')$ peak at 0.847 MeV, which has a yield of 0.0210 ± 0.0004 photons/neutron. Other iron inelastic-scattering lines are seen at 1.238, 1.408, 1.811, 2.113, 2.273, 2.523, 2.598, 2.755, 3.202, 3.663, and 4.120 MeV (lines above 4 MeV are shown in Fig. 32). Beryllium capture lines are apparent at 2.590, 2.752, 3.368, and 6.810 MeV. The broad peak around 100 keV is due to Compton downscattering in the beryllium. The total yield of escaping photons is found to be 0.146 ± 0.001 , with an average energy of 0.952 MeV.

U235+FE+BE 6.5CM+5CM+5CM

Figure 32: $^{235}\text{U} + \text{Fe} + \text{Be}$. The photon spectrum here represents the same data as in Fig. 31, except for the wider energy range; the energy resolution is 20 keV, instead of 10 keV in the previous figure. Iron inelastic-scattering lines are seen at 0.847, 1.238, 1.408, 1.811, 2.113, 2.273, 2.523, 2.598, 2.755, 3.202, 3.663, and 4.120 MeV. There is also a conspicuous iron neutron-capture line at 7.64 MeV, with a total yield of 0.00094 ± 0.00008 photons/neutron. Beryllium capture lines are apparent at 2.590, 2.752, 3.368, and 6.810 MeV.

U235+FE+BE 6.5CM+5CM+5CM

Figure 33: $^{235}\text{U} + \text{Fe} + \text{Be}$. The neutron leakage spectrum is similar to that from other beryllium-reflected critical assemblies. The same minima due to beryllium elastic-scattering resonances are apparent, at 0.63, 0.82, and 2.7 MeV, as is the tremendous increase at low energies due to reflection. The total yield of neutrons amounts to 0.562 ± 0.001 , of which 0.0501 ± 0.0005 have energy <1 keV. The average external neutron energy is 0.729 MeV, reduced from the initial average energy of 2.039 MeV, with $\bar{\nu} = 2.580$.